A BIAS AND TEMPERATURE DEPENDENT NOISE MODEL OF HETEROJUNCTION BIPOLAR TRANSISTORS

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Abstract

A bias and temperature dependent HBT noise model based on an extension of the van der Ziel noise theory is presented. An extrapolation technique is applied to the noise model that is valid for the entire bias and temperature operating range of the HBT given experimental data for a single reference condition.

Introduction

Classical noise models [1,2,3] have serious deficiencies when applied to microwave HBTs such as neglect of correlation, exclusion of collector delay time, and other subtle factors. Furthermore, these models do not lend themselves readily to applications where bias and temperature dependencies are important. The present model overcomes these limitations

A bias dependent noise model is advantageous for LNA applications because it introduces another degree of freedom for design optimization, namely bias 'tuning' that can be used in conjunction with the traditional input circuit tuning. Furthermore, since HBT-based LNAs may operate under variable bias conditions, it would be useful to predict the sensitivity of such an amplifier under this condition.

Circuits based on solid state components often are exposed to a wide ambient temperature range. To predict the performance of an LNA utilizing HBTs over such a range one must employ a device model capable of representing the variation of signal and noise performance over that temperature range. Contemporary bipolar noise models do not explicitly take temperature into account.

Measurement of noise parameters over an extended bias and temperature range is a time-consuming and expensive operation. A unique feature of our model is that, given only the measured small-signal parameters at a *single* reference bias and temperature operating point, one can extrapolate the noise parameters to any other bias and temperature operating point with an accuracy sufficient for design purposes. This is made possible because the noise generating mechanism in a bipolar transistor, unlike that of the FET, can be expressed entirely in terms of small-signal parameters, bias conditions, temperature, and frequency. Although the model was designed for application to HBTs, with minor modifications it will apply to other types of bipolar transistors.

Description of circuit model

The noise model, itself, is based on the classical van der Ziel [1] approach, but with several modifications to improve its accuracy for microwave HBT applications. These improvements include emitter-collector noise correlation, collector phase shift, the Kirk effect, emitter-base bandgap discontinuity and other more subtle factors. Unjustified simplifications of some noise models being applied to HBTs, for example, the models of Hawkins [2] and Fukui [3] are avoided.

The present model, unlike a Spice-based model which requires a multiplicity (some 40 or more) technological and design parameters, is based on a minimum set of such data (a maximum of 6). It also differs from bias and temperature models obtained from a large set of measurements covering the entire range of operating conditions, because it is based on measurements taken at one operating point only. Finally, unlike analytic models derived from curve fitting to a multiplicity of data points, which lack generality, this model is based on device physics yet firmly "anchored" to experimental data specified for a reference starting point.

The equivalent circuit used, Fig. 1, is a rather general one and is applicable to packaged and chip devices. The shaded subcircuit in Fig. 1 represents the intrinsic or "primitive" portion of the HBT. The principal bias and temperature dependent parameters are the emitter junction capacitance C_e and resistance R_e , the collector junction capacitance C_i and resistance R_c, the collector feedback or fringing capacitance C_{bc}, the current gain delay time τ and intrinsic cutoff frequency $\omega_{\alpha,i}$, and the current gain factor α_0. In addition to these elements, the parasitic resistances R_{e1}, R_{b1}, R_{b2}, R_{c1}, and R_{c2} are modeled as temperature dependent elements.

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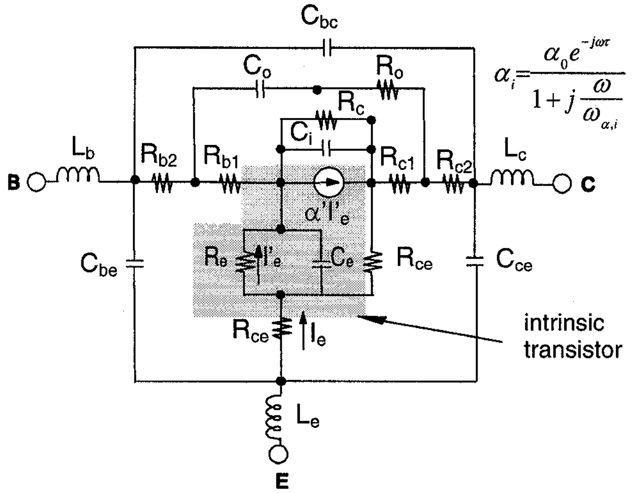


Figure 1 Small-signal circuit model for the HBT showing intrinsic portion in gray background

We follow the van der Ziel model for the intrinsic shot noise sources. These are indicated in Fig. 2 as sources j_1 and j_2 across the internal base-emitter terminals and collector-emitter terminals respectively. However, several modifications are made to the original model. These include (1) inclusion of correlation between the noise sources, (2) inclusion of collector and base transit times in the noise current gain, and (3) modification of the noise current gain expression to insure the proper limiting value of the base noise at zero frequency. The details of these modifications will be discussed in the presentation.

Both of the noise sources and their correlation are bias and temperature dependent. The corresponding mean square values are given by the expressions

$$<j_1 j_1^*> = \left[4kT\,\mathrm{Re}\left\{(1-\alpha_n)y_{11}^b\right\}\right]B \tag{1a}$$

$$<j_2 j_2^*> = 2qI_c B \tag{1b}$$

$$<j_1^* j_2> = -\left(2kTy_{21,n}^b + 2qI_c\right)B \tag{1c}$$

where <> denotes the time (or statistical average) over a noise band B, y_{jk}^b the admittance parameters of the intrinsic HBT in the common *base* mode, and α_n the noise current gain given by

$$\alpha_n = \frac{\alpha_{DC}e^{-j\omega\tau}}{1+j\dfrac{\omega}{\omega_{\alpha,i}}} \tag{2}$$

The asterisk in (1) denotes the complex conjugate. Note that the y-parameters depend on bias *and* temperature. Thus the intrinsic noise sources are functions of bias as well as the absolute temperature T.

In addition there are thermal noise sources associated with the parasitic resistances. These can be represented as voltage noise sources in series with each resistance with mean square value given by

$$<e_k e_k^*> = 4kTR_k(T)B \tag{3}$$

where the subscript denotes a particular resistor. Obviously these sources are temperature dependent.

The correlation matrix approach [4, 5] is used for all noise computations, therefore, circuit complexity is not a problem.

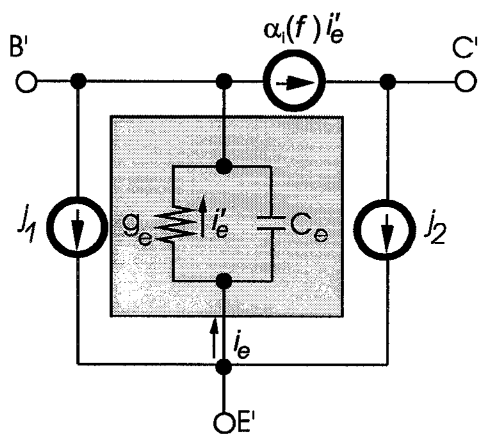


Figure 2 Noise model for the intrinsic HBT showing correlated base and collector shot noise sources j_1 and j_2

The noise extrapolation model

The terminal bias parameters used in our bias/temperature dependent extrapolation noise model are the terminal base and collector bias currents I_b and I_c, and the terminal base-emitter and collector-emitter bias voltages V_{be} and V_{ce}. We define this set of bias variables symbolically as $B = (V_{be}, I_b, V_{ce}, I_c)$.

Based on theoretical principles describing the device operation, one can derive modeling formulas for all of the bias/temperature dependent equivalent circuit parameters of the HBT. Let $P_s(T)$ and $P_s(B,T)$ denote the temperature dependent and bias and temperature dependent model elements at the (s)tarting or reference bias and temperature state. These starting values can be obtained, for example, by fitting the measured HBT S-parameters to the equivalent circuit model with any one of many optimization procedures commonly used in the field.

These starting values, in conjunction with the analytically or empirically derived element formulas, are used to express the element values at any other bias and temperature state. This extrapolation procedure can be described symbolically by the expressions

$$P(B, T) = F(P_s, B_s, T_s, B, T) \qquad (4a)$$

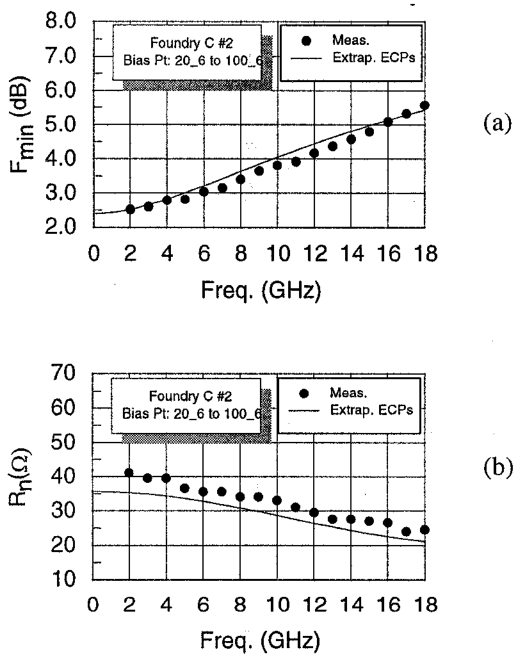
$$P(T) = F(P_s, T_s, T) \qquad (4b)$$

where P denotes the new value of the small-signal parameter in question and F represents the functional dependence of the parameter on temperature and bias derived from theoretical or empirical considerations.

An example illustrating this procedure is the formula for the bias-dependent depletion layer component of the emitter junction capacitance C_t at some arbitrary operating bias I_c and temperature T given explicitly in terms of its value C_{ts} at the reference bias corresponding to the collector current I_{cs}.

$$C_t = \frac{C_{ts}}{\sqrt{1 - \left(\frac{C_{ts}}{C_o}\right)^2 \frac{kT}{q} \ln\left(\frac{I_c}{I_{cs}}\right)}} \qquad (5)$$

This formula for the step junction model of the emitter junction, is based on the junction I-V relation expressing the dependence of emitter current on emitter junction voltage. Here k and q denote Boltzmann's constant and electron charge, respectively, and C_o refers to the usual junction capacitance constant for the step junction containing the base doping constant and emitter junction area.



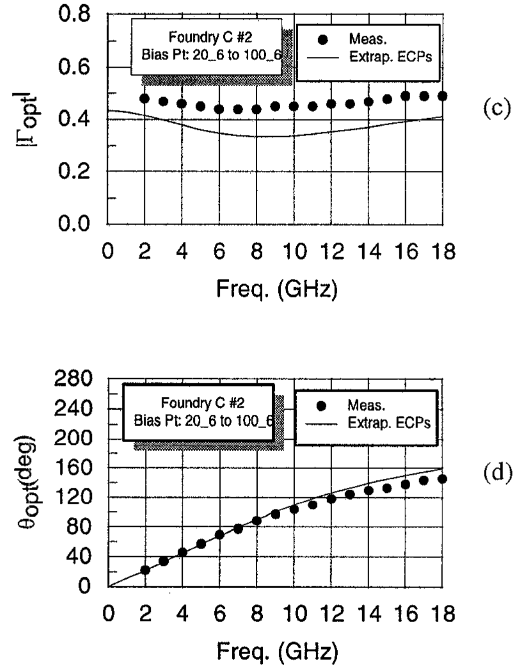


Figure 3 Extrapolation over a temperature range (a) F_{min}, (b) R_n, (c) $|\Gamma_{opt}|$, and (d) θ_{opt}

Examples of model application

Figure 3 is an illustration of the goodness of extrapolation between a reference bias, denoted as 20_6, corresponding to room temperature operation, and the corresponding extrapolated operating point 100_6 at $T = 100^o$C — an 80^o jump. Shown are comparisons of the predicted and measured frequency dependence of the four terminal noise parameters.

Figure 4 is another example. In this case two successive levels of extrapolation are modeled, one in temperature (the same as in Fig. 3) plus an additional jump in base current from 100μA to 500μA, an approximate factor of five increase in collector current.

It is evident that the extrapolation in both cases, though not exact, is remarkably good and should be adequate for design purposes.

Summary and conclusions

We have demonstrated a simple, but accurate bias/temperature dependent noise model of the HBT. The model overcomes limitations of present models in that it explicitly includes bias and temperature dependencies. Firmly based on the physics of noise generation in bipolars, it requires input data at only one operating point from which accurate extrapolation of the small signal parameters, hence noise parameters, can be made to any other operating point of the HBT in its useful range.

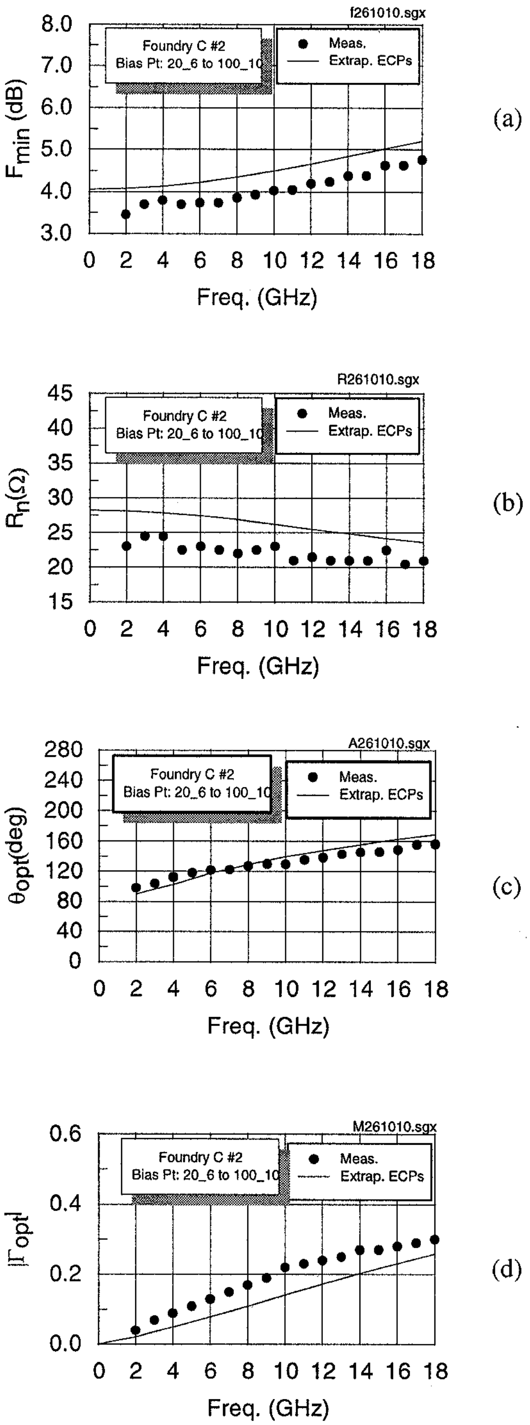


Figure 4 Extrapolation over a bias and temperature range (a) F_{min}, (b) R_n, (c) $|\Gamma_{opt}|$, and (d) θ_{opt}

Our noise model is distinguished from other approaches which either require more material and design parameters or a multitude of measurements, or which lack generality of application. It can be used as a stand-alone computer program or integrated into any microwave circuit simulator.

These features should be of interest to any designer of HBT-based LNAs requiring operation over an extended bias and temperature range.

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